INVESTIGATION OF SEDIMENT TRANSPORT THROUGH AQUATIC VEGETATION USING LARGE-SCALE HIGH-FIDELITY TURBULENCE SIMULATIONS

Allocation: Illinois/680 Knh
PI: Rafael Tinoco Lopez[1]
Co-PI: Paul Fischer[1]
Collaborators: Som Dutta[1], Pallav Ranjan[1]

[1]University of Illinois at Urbana–Champaign

EXECUTIVE SUMMARY

Turbulence generated by aquatic vegetation in fluvial and coastal systems drives changes in the hydrodynamics and sediment mechanics within aquatic ecosystems. It is expected that plants extract energy from the flow, reducing near-bed flow velocities, thus damping erosion. However, turbulence generated by vegetation patches can actually enhance resuspension and transport under the right conditions. This study uses direct numerical simulations (DNS) and large-eddy simulations (LES) through various arrays of idealized vegetation, represented as cylinders, to increase the understanding of the interactions among vegetation, flow, and sediment. Simulations are conducted using the higher-order spectral element-based computational fluid dynamics (CFD) solver Nek5000. Staggered arrangement of cylinders mimicking an actual experimental setup have been simulated to shed light on the details of flow features and suspended sediment distribution as a function of flow, plant, and patch characteristics, thus increasing the understanding of different hydro- and morphodynamic processes.

RESEARCH CHALLENGE

Vegetation patches in rivers and coastal areas act as ecosystem engineers to modify various aspects of their own ecosystem [1]. Aquatic vegetation provides a wide range of ecosystem services [2], from nutrient uptake and oxygen production to habitat creation to bed stabilization and even carbon sequestration and nutrient farming. Owing to computational limitations, past computational studies have mostly focused on using CFD models based on Reynolds averaged Navier–Stokes equations, which only provide an averaged approximation of the flow field. The few studies that have used high-fidelity LES have been limited by the number of vegetation elements that can be modeled. Further, the number of both experimental and numerical studies investigating vegetation–flow–sediment interactions is still very limited. Most of the existing data in this area come from laboratory experiments [3] that recreate conditions closer to nature but often lack the spatial and temporal resolution required to capture some fundamental processes in detail.

This study is coupled with experimental research currently being conducted at the Ven Te Chow Hydrosystems Laboratory and the Ecohydraulics and Ecomorphodynamics Laboratory at the University of Illinois at Urbana–Champaign. The study conducts numerical simulations at an unprecedented scale, resolving details that in conjunction with the experiments will provide as yet unknown insights into the fundamental dynamics of flow and transport in the presence of aquatic vegetation [4]. These large-scale computations will help improve lower-order models of the processes while also informing better experimental design and measurement practices. The number of computation points required to model the whole domain is near 1.2 billion, making the study a unique opportunity because of the scale and complexity of the processes investigated. While such simulations are still tractable on a petascale platform such as Blue Waters, the computational cost is too high, resulting in a reduced number of modeled scenarios, which constrains the insights that a broader range of parameters could yield.

METHODS & CODES

The research team conducted high-resolution LES and DNS of the flow at different configurations of the idealized vegetation using the open source, spectral element-based high-order incompressible Navier–Stokes solver Nek5000 [5,6]. Sediment transport was modeled under the Eulerian framework using the advection–diffusion equation [7], making this study one of the first to look at the complex interaction among sediment–flow–vegetation using high-fidelity CFD simulations.

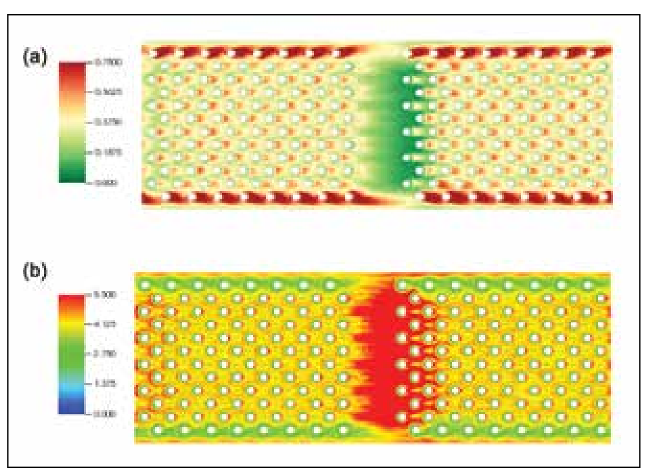

Figure 1: Near-bed nondimensional (a) turbulent kinetic energy field and (b) suspended sediment concentration distribution. The sediment deposition pattern on the channel bed is governed by the local level of turbulence in the region. Regions of low turbulence (gap) are marked by a higher concentration of suspended sediment.

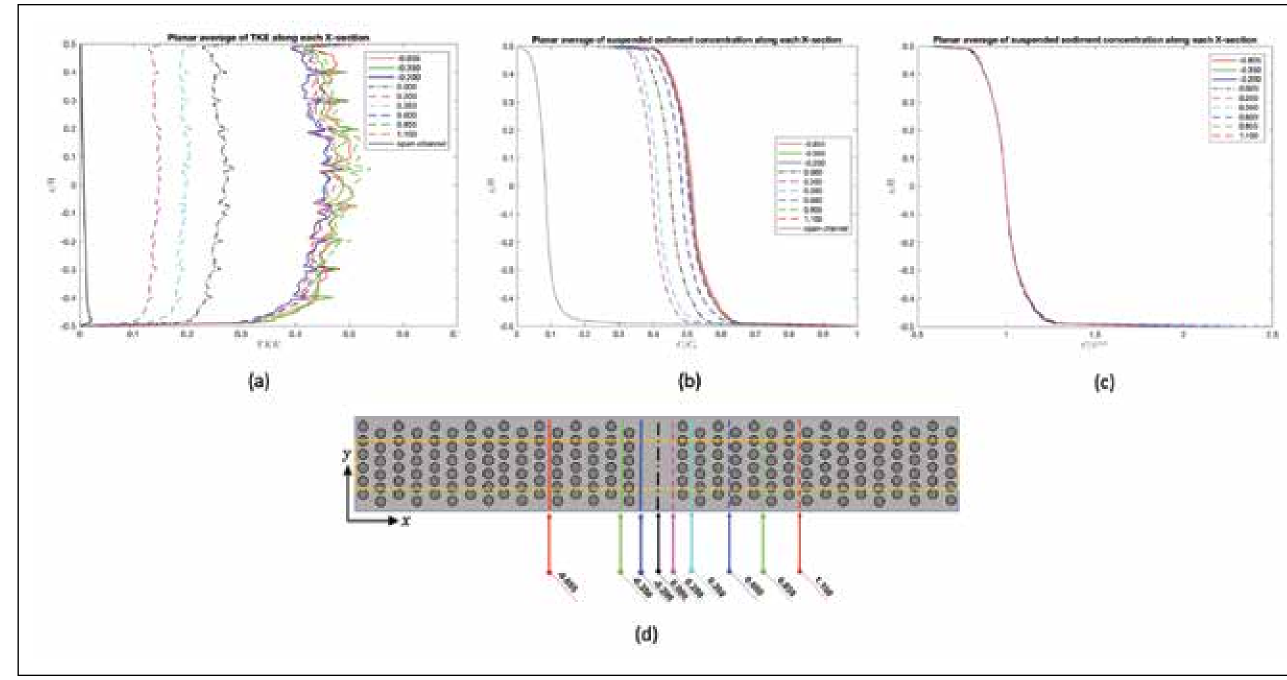

Figure 2: Time- and space-averaged vertical profiles of normalized (a) turbulent kinetic energy, (b) suspended sediment concentration (SSC) normalized using near-bed values, and (c) SSC normalized using volumetric concentration; (d) shows lateral cross-sections corresponding to vertical profiles in (a–c).

RESULTS & IMPACT

The research team conducted three-dimensional LES for a range of Reynolds numbers between 8,000 and 20,000 for a staggered array of rigid cylinders. The first part of the study focused on understanding hydrodynamic changes to the flow field owing to the presence of an emergent vegetation array compared to existing experimental data. To allow for access of measuring probes in laboratory experiments, a section of a vegetation patch is often cleared out, resulting in a small gap where the measurements are taken. The team has proven that measurements within such a gap may not be representative of flow within the patch (Fig. 1). An optimal dimension of a gap in the vegetation can be found such that experimental measurements of flow statistics within it are representative of the flow field within the array. Simulations focused on suspended sediment concentration highlighted that turbulent kinetic energy is the governing factor in erosion, resuspension, and transport of suspended sediments in vegetated flows. This suggests that the equilibrium boundary condition used for simulating suspended sediment transport in nonvegetated channel flows should be modified to account for local erosion and deposition based on turbulent kinetic energy rather than mean shear stress (Fig. 2).

These findings will improve the estimates of sediment transport in natural water bodies, allowing for better sediment management strategies for rivers, ports, and harbors. Simulations were conducted using up to 90 million computational points, running on 8,196 processors at a time, which would be unfathomable without the use of a petascale supercomputing facility such as Blue Waters.

WHY BLUE WATERS

The study pushes the limit of the scale at which high-resolution simulations are used to study complex multiphase flow in environmental fluid mechanics, requiring computational resources with sustained computing power at an unprecedented scale such as Blue Waters. Simulations have been conducted for up to 296 million computational points, with the code scaling strongly up to 32,768 Message-Passing Interface ranks. Without access to petascale high-performance computing resources, completing the study within a realistic timeframe would be impossible. In addition, since visualization of a phenomenon is an effective way to understand and explain its mechanics, the team will continue to work with Blue Waters project staff to create animations using data from the simulations.

PUBLICATIONS & DATA SETS

P. Ranjan, "High-resolution numerical investigation of hydrodynamics and sediment transport within emergent vegetation canopy," *Diss.*, 2018.

P. Ranjan, S. Dutta, K. Mittal, P. F. Fischer, and R. O. Tinoco, "Flow and sediment transport through aquatic vegetation," in preparation for *J. Fluid Mech.*, 2019.